

STUDY OF PHOTON EMISSION BY ELECTRON CAPTURE DURING SOLAR NUCLEI ACCELERATION: I. TEMPERATURE-DEPENDENT CROSS SECTION FOR CHARGE CHANGING PROCESSES.

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1. INTRODUCTION. The study of charge-changing cross-sections of fast ions colliding with matter provides the fundamental basis for the analysis of the charge states produced in such interactions. Given the high degree of complexity of the phenomena, there is no theoretical treatment able to give a comprehensive description. In fact, the involved processes are very dependent on the basic parameters of the projectile, such as velocity v , charge state q and atomic number Z , and on the target parameters Z_t , q_t , the physical state (molecular, atomic or ionized matter) and density. The target velocity, v_t , may have also incidence on the process, through the temperature T of the traversed medium. In addition, multiple-electron transfer in single collisions intricates more the phenomena. Though, in simplified cases, such as protons moving through atomic hydrogen, considerable agreement has been obtained between theory and experiments, however, in general the available theoretical approaches have only limited validity in restricted regions of the basic parameters. Since most measurements of charge-changing cross-sections are performed in atomic matter at ambient T , models are commonly based on the assumption of targets at rest ($T=0$); however at Astrophysical scales, T displays a wide range in atomic and ionized matter. Therefore, due to the lack of experimental data we attempt here to quantify T -dependent cross-sections on basis to somewhat arbitrary, but physically reasonable assumptions.

II.- CHARGE TRANSFER IN FINITE-TEMPERATURE MATTER. Let introduce the relative velocity

$$V_R = v + v_t \quad [1]$$

in the kinematics of the collision, where the target velocity, v_t , is the most probable thermal velocity of free electrons or hydrogen atoms in ionized or atomic matter respectively. If v_t is fixed in (1), for instance at $v_t=0$, the dependence of charge-changing cross sections on the projectile velocity behaves as is shown in pannel-1, for hydrogenic ions in atomic hydrogen, where σ_{pc} =loss cross-section, σ_{cc} =Coulomb capture cross-section and σ_{cr} =radiative capture cross-section. A rough interpretation of that velocity-dependence may be seen in terms of the idealized "free-collision approximation" (though the Born approximation which allows for screening effects gives qualitatively the same description): electrons are preferentially captured into states of orbital velocities $u \sim v$ and preferentially lost at $v > u$. Since the impact parameter behaves as $q q_t / M v^2$, where M is the reduced mass, σ_{pc} at $v > u$ decreases with v , whereas at $v < u$, σ_{pc} increases with v because the adiabatic nature of the collision. Similarly, since the capture radius $R_c \sim 1/v^2$, electron capture declines

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with the projectil velocity. At relatively low v when R_c is large, electrons are readily captured far from the nucleus, where the energetic levels are very closed among them, falling much probably in an allowed state. So, there is photon emission because the electron braking in the capture; this is called Coulomb Capture. When v is relatively high, electron binding takes place at small R_c , where the energetic states are widely separated: the probability is high for the electron to fall in a forbidden state, such that a photon is emitted for the electron to be placed in an allowed orbit; this is known as Radiative Capture. Obviously, σ_{cr} at low v and σ_{cc} at high v are not null. According to [1], at Kinetic Energies $E \gtrsim 9 \text{ MeV/n}$, σ_{cr} becomes predominant over σ_{cc} . It can be seen in (1), from V_R , that Coulomb capture in plasmas ($T \gg 0$) becomes a rare process, even at low v , because the electron thermal v_t is quite significant. Now let fix v in (1) to analyze the temperature behavior of cross-sections: for electron capture in atomic gas ($T < T_i$, = ionization temperature of the target medium) it is expected that cross-sections increase with the increase of the target T , because the binding energy of the atomic target electrons decline with T , so that when the electronic clusters of the projectil and target come close, it is easier to pick-up a target electron. At $T > T_i$, when the "free-collision approximation" is near to occur, the T -dependence of cross-sections is similar to the v -dependence, because the increase of V_R with the subsequent decrease in R_c . In the limit of high energy particles in high- T plasmas only σ_{cr} is significant. The point $\sigma_{cc} = \sigma_{cr}$ is reached at lower ion energies than 9 MeV/n as T increases ($E_{\text{impact}} = E_{\text{ion}} + E_t = 9 \text{ MeV/n}$). For electron loss, the effect of T on σ_{pc} may be seen as a shift in energy, in the sense that, a given value of σ_{pc} is reached at lower ion velocities as T increases. Although it is not expected a noticeable change in σ_{pc} in ionized with respect to atomic H, because the electronic screening of the target nuclei is negligible relative to the ionization potentials in the projectil ions, however, the increase of the medium- T increase the impact energy, and so σ_{pc} is affected: for a fixed v in the range $v > u$, σ_{pc} decreases with T because collisions take place at smaller impact parameters, while in the range of adiabatic collisions ($v \lesssim u$), σ_{pc} at a fixed v increases with T . This is rather seen in atomic media, since a relatively high T the Thermal velocities are high, such that $V_R \gtrsim u$, in which case, as we said before the T -dependence show the same behavior as the v -dependence.

III. METHODS AND RESULTS. Our analysis here is limited to the case for which projectil ions are accelerated from the background thermal matter, so that their initial velocities and initial charge states correspond to thermal temperatures. For the local charge states, Q_L , we are mainly based on the Solar-System ionization fractions in [2]. We arbitrarily assume that the accelerated ions undergo charge equilibrium in the source (solar flare matter), such that the charge evolves according to the effective charge $q^* = Z[1 - \xi \exp(-130\beta/Z^{0.66})]$, with $\beta = v/c$ and $\xi = \exp[-130(kT/mc^2)]$ k =Boltzman constant and m the hydrogen or the electron mass depending on whether $T \lesssim T_i$ or $T > T_i$. Normalization of Q_L with q^* is made by means of

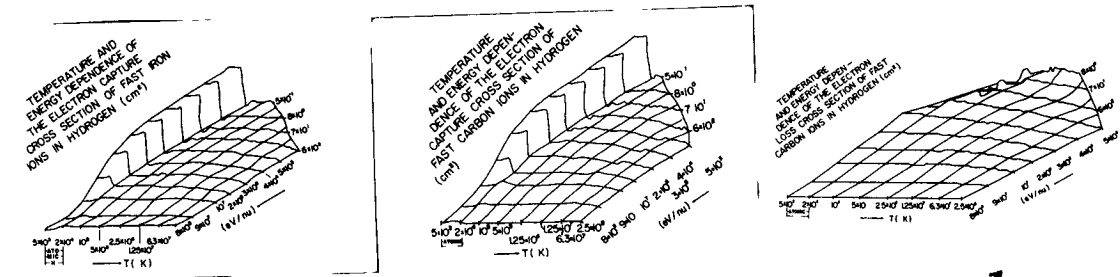
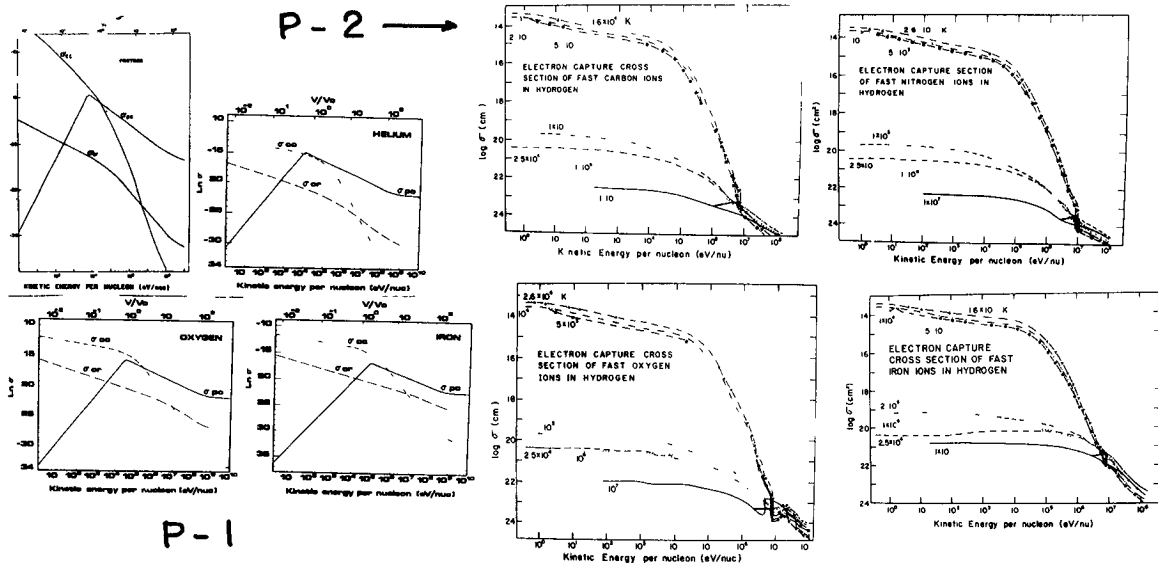
$q = [(Z - Q_L)(q^* - q_{th}^*) / (Z - q_{th}^*)] + Q_L$, where q_{th}^* is the effective charge of the accelerated ions where they are at thermal velocities. For the electron binding in atomic H we assume that the attractive potential is of the form $U_C \psi(T)$, where U_C is the Coulomb Potential and $\psi(T) = 1 - \exp(-T_i/T)$. To account for the increase of capture cross-sections with T we divided the prevailing cross-sections in atomic media ($T \approx 0$) by $\psi(T)$, with $T_i = 2.5 \times 10^4$ K. At $T > T_i$ there is an abrupt fall in the capture cross sections because the drastic change in v_t from atomic to electron thermal velocity. For $T < T_i$ in panels 2-3 we plotted $\sigma_{cc}/\psi(T)$ at $E_{\text{impact}} < 9 \text{ MeV/n}$ and $\sigma_{cr}/\psi(T)$ at higher energies. Due to the predominance of σ_{cr} in plasmas, for $T > T_i$ we plotted $\sigma_{cr}/\psi(T)$ with T fixed at 2×10^4 K. The cross $\sigma_{cc} = \sigma_{cr}$ is indicated by a transversal solid line. For σ_{pc} we introduced, as in electron capture cross-sections, the normalized charge and V_R instead of v , and we ran it for any T value (panels 4-5). We employed the conventional temperature-independent cross-sections for atomic matter: so, for atomic sources of solar particles we have according to [3] that, for highly charged nuclei ($q \ll Z-1$) $\sigma_{cc1} = \pi a_0^2 q^2 Z_t^* 2^{1/3} (v_0/v)^9 (1 + 4Z_t^{*2} v_0^2/v^2)^{-4}$ and according [4] $\sigma_{pc1} = \pi a_0 q^{-3} Z^{4/3} Z_t^{2/3} (v/v_0)^2$ if $v < v_1$, or according to [5] $\sigma_{pc2} = \pi a_0^2 q^{1/3} Z_t^2 (v_0/v)^3$ if $v > v_1$, where v_1 corresponds to $\sigma_{pc1} = \sigma_{pc2}$. For very high velocities, when nuclei become hydrogenics, according to [5] we have $\sigma_{pc3} = 4 \pi a_0^2 Z^{1/3} Z_t^2 (v_0/v)^3$, ($v > Z v_0$), and according [3] $\sigma_{cc2} = \pi a_0^2 Z^5 Z_t^{*5} (2v_0/v)^{12} (1 + 4Z_t^{*2} v_0^2/v^2)^{-4}$. The case of low velocity hydrogenic heavy ions in atomic media has only a meaning when particles are injected into the acceleration region from a preliminary acceleration stage, so it is excluded within the present context. At high T , in sources of ionized H, we used σ_{pc1} and σ_{pc2} with q instead of Z , and according to [6], $\sigma_{cr1} = 6.15 q^2 q^4 (v_0/c)^3 (v_0/v)^2 (v_0/v^2 + q^2 v_0^2)$ if $v \ll 3 q v_0$ and $\sigma_{cr} = 9.1 \times 10^{-21} (q^2 v_0^2/v^2 + q^2 v_0^2)^2 (q^2 v_0^2/v^2) \exp[-(4 q v_0/v) \arctg(v/2v_0)] / [1 - \exp(-2 \pi q v_0/v)]$ if $v > 3 q v_0$; for hydrogenic ions (very high T or v) we used according to (5) $\sigma_{pc4} = \pi a_0^2 Z^{-5/3} Z_t^{1/3} (v/v_0)^2$ if $v < v_2$ and σ_{pc3} if $v > v_2$, where v_2 correspond to $\sigma_{pc3} = \sigma_{pc4}$. Obviously, at $E_{\text{impact}} > 9 \text{ MeV/n}$ in sources of atomic H, we used σ_{cr} instead of σ_{cc1} or σ_{cc2} . It can be noted that due to continuous changes of the normalized q , there are oscillations in the cross-section values, that for reason of scale can not be smoothed at high energies as easy as in low energies.

IV. CONCLUSIONS. Under the arbitrary assumption that electronic screening of the target H is not very important compared with the screening of the projectile ions, we extrapolate charge-changing cross sections in atomic matter at $T \approx 0$ to finite temperature media, by introducing the target velocities. Nevertheless, for atomic media we have considered the effect of the target electronic screening on capture cross-sections, as T increases. We feel that the obtained results are of more realistic nature, for astrophysical goals, that the mere extrapolation of the conventional T -independent cross-sections.

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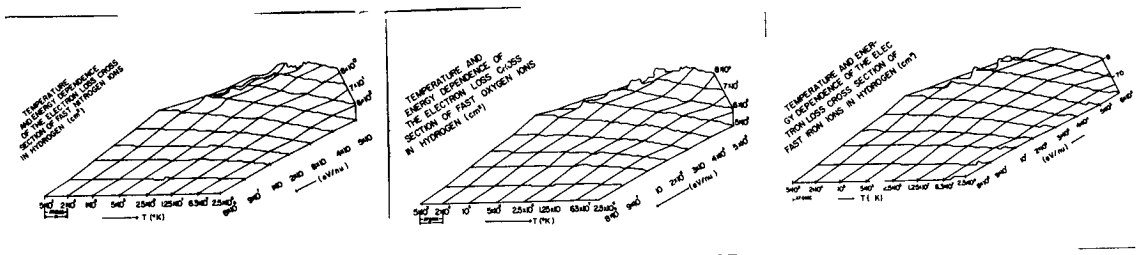
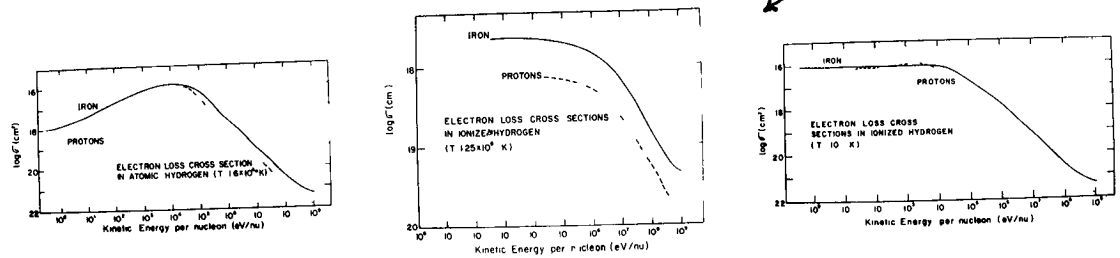
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